A SEARCH FOR FREE QUARKS IN DEEP INELASTIC MUON SCATTERING

The European Muon Collaboration

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ABSTRACT

A search was made at the CERN SPS for long-lived fractionally charged particles produced in deep inelastic muon interactions on a Be target using the existing muon beam line as a spectrometer. No such particles were found, leading to upper limits for the production cross-section of the order of 10^{-36} cm² for 200 GeV incident muon momentum and quark masses below 9 GeV for the 2/3 charge and 15 GeV for 1/3 charge.

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1. Introduction

The search for fractionally charged particles in different reaction mechanisms is important since evidence for fractional charge on matter has been reported [1,2] and there is no theoretical principle which forbids the existence of free quarks.

Previous quark searches at accelerators have been carried out mainly in hadronic interactions [3,4,5,6,7,8], whereas few have been made in high energy electromagnetic and weak interactions [3,9,10,11]. We report here on the first search for fractionally charged particles in deep inelastic muon scattering using the SPS muon beam both as a source of high energy muons (200 GeV) and as a spectrometer to measure the outgoing momenta. In addition the dE/dx and time of flight of the produced secondary particles were measured.

The use of the muon beam to search for quarks has the following advantages:

- i) deep inelastic events show evidence that quark jets are the origin of hadronic final states in the current direction,
- ii) it is possible to achieve a high sensitivity since the quark parton model works well down to very low Q^2 , therefore the majority of muon interactions are potential quark producers,
- iii) although the solid angle is small the spectrometer nevertheless has good acceptance along the current (quark) direction.

2. Experimental Conditions

The experiment was performed using the muon beam-line M2 in the CERN SPS North Area [12].

Pions and kaons produced by 400 GeV primary protons and their decay muons are transported along a 600 m long FODO channel tuned to 200 GeV and are focused onto a 1 m long Be target (fig. 1). The second part of the muon beam line is used as a spectrometer with a momentum acceptance of $\Delta P/P = \pm 10\%$ and the solid angle of 8 μ sr. Although this is a rather small acceptance it matches well the concept of the quark following the direction of the virtual photon for large W as shown in fig. 2.

Three different momentum settings of the experiment were used: two for super-momentum particles (+250 GeV and -250 GeV) and one for particles of lower momentum (-50 GeV). The super-momentum technique uses the fact that a quark of charge N_e and momentum p will behave in a magnetic beam channel like a particle of integral charge and momentum p/N_e since the deflection of charged particles by magnetic fields is proportional to N_e/p .

As the ionization (and hence the energy loss dE/dx) of a charged particle is proportional to the square of its electric charge a quark passing through a plastic scintillator would be detected by its anomalously low ionization. The energy loss dE/dx was therefore measured in six pairs of scintillation counters (fig. 1), distributed over a length of 60 m in the beam line starting 330 metres downstream of the Be target. Each pair consisted of a 'big' (B) scintillator with dimensions $15 \times 15 \times 2 \text{ cm}^3$ and a 'small' (S) scintillator $12 \times 12 \times 2 \text{ cm}^3$.

The S counters were used as trigger counters, and the pulse-heights in the B counters were analyzed whenever the trigger conditions (see below) for the S counters were satisfied. With this procedure the probability to observe a pulse height in the small ionization region (a 'quark' signal) coming from statistical fluctuations in the photomultiplier or from edge effects in the scintillator is strongly suppressed. Furthermore, in order to avoid coincidences resulting from particles hitting the lucite light guides, the S and B counters were oriented with the phototubes orthogonal to each other.

The HV levels for all the counters were individually adjusted to the same output value for a minimum ionizing particle (MIP) and the threshold (10% of a MIP) applied to the S counters was derived from attenuation curves. The average pulse height resolution of the counters was $\sigma_{PH} \sim 12\%$. The response of plastic scintillator is linear down to levels less than one tenth of minimum ionization. It was easy to calibrate the quark detection counters by switching the muon beam to normal operation at any time during the data taking period. Furthermore the stability of each counter was continuously monitored via ADC spectra taken with an unbiased trigger defined by the six-fold coincidence of the S counters without any further condition. The curve C in fig. 3 show the pulse height spectra for the B counters, obtained during the data taking with this unbiased trigger.

The trigger 'Q' for a fractionally charged quark is defined by the six-fold coincidence of the S counters when a pulse height less than 60% of the pulse from a MIP was observed in each of them. With this logic a value of $5 \cdot 10^{-14}$ Q triggers per incident proton on the primary target was obtained under normal muon beam line operation.

For each satisfied trigger condition the pulse heights of all B counters were recorded using the EMC data acquisition system [13]. For the three different spectrometer settings, +250 GeV, -250 GeV and -50 GeV, the integrated proton flux taken was $5.7 \cdot 10^{15}$, $2.0 \cdot 10^{15}$ and $1.1 \cdot 10^{15}$ respectively. In order to derive the corresponding muon fluxes the muon momentum spectrum at the Be target has been calculated using the HALO program [14] and is shown in fig. 4. Integrating the spectrum gives $8 \cdot 10^{-5}$ muons per incident proton at the Be target within a momentum band of $100 < p_{\mu} < 220$ GeV. As the Be target is placed inside a vertical bend, quarks produced by muons in the low momentum tail of fig. 4 have a smaller probability to be accepted by the spectrometer stage as they are produced at finite angles.

The total amount of material along the beam line, from the downstream edge of the Be target up to the last counter, was 0.75 proton collision lengths, $0.58 L_{\text{coll}}$ for the scintillator (32 cm in total) of the B + S counters and the beam momentum station counters, the rest for air (86 m) along the beam line. The remaining 306 m of the spectrometers was equipped with vacuum pipes.

Finally, three general comments should be made:

- a) our apparatus is sensitive to all fractional electric charges between $0.2 < |q| < 0.7$ which limits are determined by the lower and upper trigger levels;
- b) if the quark lifetime is much smaller than 10^{-8} sec the detection efficiency of our experiment would be seriously reduced due to the 360 m long distance quarks have to travel before they can be detected.
- c) if quarks have an anomalously high interaction cross-section, the sensitivity of our experiment would be reduced due to the amount of material along the quark path.

3. Results

The combined effect of using the super-momentum technique and the long lever arm of the spectrometer resulted in a clean sample of events recorded during the data taking. With the spectrometer set at +250 GeV, -250 GeV, -50 GeV we obtained 275, 15 and 16718 'Q' triggers respectively. In fig. 3 the pulse heights for the individual six B counters obtained with these triggers (curve A) are shown for the configuration (+200, +250 GeV).

The dotted lines are, as explained before, the pulse heights for the unbiased trigger, scaled down by a factor 5200. Most events obtained with the quark trigger tend to cluster around the charge one region, therefore these are normal integrally charged particles that escaped the trigger selection. Very few of the pulse heights are in the low ionization region; the curve B drawn for the first counter shows the signal expected for $2/3e$ charged particles crossing the counter (the resolution assumed is the same as for the minimum ionization peak).

There is no event with more than one of its six pulse heights less than 75% of minimum ionizing. From this we conclude that no evidence of any quark candidates occur in our data.

In order to extract a limit for the quark production cross-section the acceptance of the spectrometer had to be determined. For this purpose we used a Monte Carlo program simulating muon deep inelastic events and then tracking the particles produced through the spectrometer section of the beam line. The assumption was made that the produced quarks have direction and energy of the virtual photons produced by the incident muons. Using the Monte Carlo program (because no detection of the scattered muons was performed) the mean Q^2 of the reaction was found to be $\langle Q^2 \rangle \sim 1 \text{ GeV}^2$ and W^2 is in the range $300 < W^2 < 400 \text{ GeV}^2$ with a mean value of about $\langle W^2 \rangle = 390 \text{ GeV}^2$. These kinematics values have been calculated for events where the quark (virtual photon) would be accepted by the spectrometer. In order to evaluate up to which quark masses our experiment was able to detect we have taken into account the time gate of the trigger (110 ns), the flight path of the particle and the momentum window defined by the spectrometer setting. Our results are then valid for quark with masses up to 9 GeV for $2/3$ charge quarks and 15 GeV for $1/3$ charge quarks assuming no threshold suppression of the production cross-section. This difference is imposed by the momentum bounds defined by the spectrometer whose

setting was 250 GeV ($\pm 10\%$). So, scaling the momenta according to the charge one has that a $2/3$ charge quark was selected by the spectrometer only if its momentum was ~ 167 GeV and for a $1/3$ charge quark this number was ~ 83 GeV. This difference in momenta is then found in the mass limit.

To evaluate the limit for the quark cross-section we used the muon fluxes and acceptances as reported in Table 1 for the two quark charges.

Central Spectrometer Momentum (GeV)	Total μ flux (10^{11})	$A_{cc}(\pm 1/3e)$	$A_{cc}(\pm 2/3e)$
+250	4.6	0.158	.204
-250	1.6	0.158	.204
-50	0.9	0.081	.110

Table 1

From these values we compute the limit for the quark cross-section per nucleon for the three conditions given in Table 2

Central Spectrometer Momentum (GeV)	e_q	Quark cross-section per nucleon σ_q (10^{-36} cm ²)	Quark momentum band (GeV)	$R_q = \frac{\sigma_q}{\sigma_\mu}$
+ 250	+ 2/3	1.20	167 ± 17	$1.2 \cdot 10^{-6}$
	+ 1/3	1.50	83 ± 8	$1.5 \cdot 10^{-6}$
- 250	- 2/3	3.50	167 ± 17	$3.5 \cdot 10^{-6}$
	- 1/3	4.50	83 ± 8	$4.5 \cdot 10^{-6}$
- 50	- 2/3	11.8	33 ± 3	$1.2 \cdot 10^{-5}$
	- 1/3	16.0	17 ± 2	$1.6 \cdot 10^{-5}$

Table 2

In order to quote ratios between these upper limits and the total inelastic muon cross-section we made use of the Weiszecker-Williams approximation [15], integrating the equivalent photon spectrum within the momentum window defined by our spectrometer. This evaluation results in a value for the inelastic cross-section $\sigma_{\mu}(\mu N \rightarrow \mu x) = 1 \mu b$, bearing in mind that this number is very dependent on the integration limits used. The ratio $R_q = \sigma_q / \sigma_{\mu}$ for the three configurations and different quark charges is reported in the last column of Table 2.

The direct comparison of our results with limits coming from other accelerator experiments is rather difficult as it depends deeply on the production mechanism assumed. However our results can be compared with the recent e^+e^- limit [11] where they report $R_q = \sigma_{qq}^- / \sigma_{\mu\mu}^{+-} \lesssim 10^{-2}$ for $M_q \lesssim 14 \text{ GeV}/c^2$ and the ν experiment [9] which gave $R = q/\nu \approx 10^{-4}$.

In conclusion, no evidence has been found for long lived particles with charges $|q| < 1$ and masses below 15 GeV, resulting in an upper limit for the production cross-section of the order of 10^{-36} cm^2 .

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Figure Captions

Fig. 1 Layout of the spectrometer section - not to scale. The position along the beam line is given in parentheses for some components. S_1 - S_6 are trigger counters, BMS are Beam Momentum Station hodoscopes.

Fig. 2 Q^2 - ν plane for 200 GeV. The shaded area corresponds roughly to the phase space of this experiment.

Fig. 3 Pulse heights for the six B counters.

curve A : quark trigger

curve B : pulse height expected by $2/3e$ charged particles

curve C : monitoring trigger (scaled by a factor 5200).

Fig. 4 Muon yield at the Be production target versus momentum.

Fig. 1

Fig. 2

Fig. 3

Fig. 4